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K_1/K^* enhancement as a signature of chiral symmetry restoration in heavy ion collision

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We discuss the meaning of chiral partners. For a vector meson, the isospin-zero and hypercharge-zero state in the flavor octet mixes with the flavor singlet state. Since the flavor singlet vector meson does not have a chiral partner, the mixed ω and ϕ mesons will not have chiral partners. This means that even when chiral symmetry is restored, these mesons will not become degenerate with their corresponding parity partners. On the other hand, the K_1 and K^* mesons are chiral partners, and both have widths smaller than 100 MeV. Therefore, we emphasize that studying these mesons in environments where chiral symmetry is restored is particularly important for understanding the effect of chiral symmetry restoration on chiral partners and their masses. In particular, we demonstrate that in heavy-ion collisions, the enhanced production ratio of K_1/K^* can serve as a key signature of chiral symmetry restoration during the early stages of the collision.

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1. Introduction

Understanding the generation of the mass of a hadron from the small quark masses is one of the fundametal puzzles of Quantum Chromodynamics (QCD). In ref [1], we showed that the mass of the vector meson will change in nuclear matter due to partial chiral symmetry restoration . The work attracted great attention as such a change can be observed from a heavy nucleus target experiment, which will provide a link to understanding the origin of hadron masses[2–6]. Unfortunately, while several experiments tried to observe the vector mass shift through electromagnetic signals from heavy ion collision and/or nuclear target experiments[7], no solid confirmation of ρ meson mass shft has been seen so far except for increased width[8]. One important drawback of measuring the ρ meson is that, while it contributes dominantly to the electromagnetic signal in the intermediate energy region, its large vacuum width, along with additional broadening in the medium, will make any realistic mass shift measurement impossible[4]. Furthermore, in addition to chiral symmetry-breaking effects, the ρ meson mass has contributions from other effects so it is hard to identify the origin of the hadron mass as generated in the vacuum in terms of underlying QCD degrees of freedom. To isolate the effects of chiral symmetry breaking, one can study the mass difference between chiral partners. However, the chiral partner of the ρ meson, the a_1 meson, has an even larger vacuum width, making any realistic measurement in the medium impossible.

The recent efforts by the E16 experiment [9, 10] to measure the ϕ meson mass through its electromagnetic decay in a nuclear target with higher statistics, compared to the previous KEK experiment[11], are very promising, particularly due to the narrow vacuum width of the ϕ meson. Furthermore, the E-88 experiment[12] will measure the ϕ meson mass shift through the K^+K^- decay. Both experiments are promising and could provide the first explicit measurement of a mass shift.

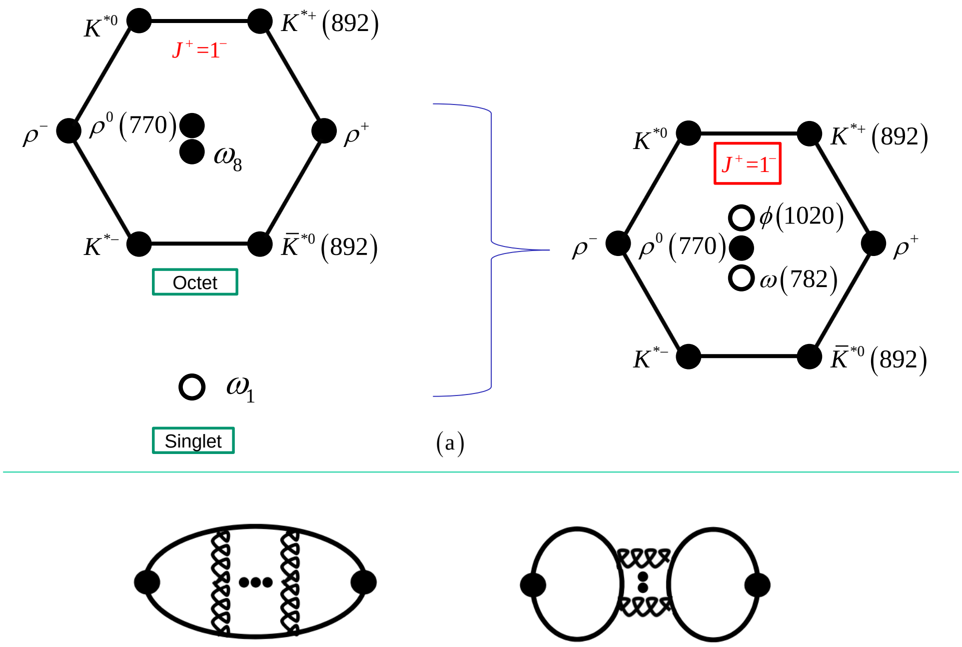
On the other hand, although very interesting, ϕ does not have an exact chiral partner per se, as will be discussed in the next section. In the following, we will discuss the meaning of chiral partners and why K_1, K^* are good candidates of chiral partners that can be realistically measured[13].

2. Flavor SU(3) symmetry and octet singlet mixing

If all the light quark masses were equal, the meson spectrum would form an irreducible representation of flavor SU(3). For meson states, this would include a flavor singlet and octet. However, because the strange quark mass is significantly larger than the up and down quark masses, the two states with zero isospin and hypercharge in the singlet and octet representations will mix. How much the octet and singlet mix depends on the nature of the particles. For the pseudoscalar mesons, the mixing is small, while for the vector mesons, it is almost ideal. The situation is depicted in Fig. 1-(a). Here the fields are as follows.

$$\begin{cases} \omega_1 = \frac{1}{\sqrt{3}}(\bar{u}u + \bar{d}d + \bar{s}s) \\ \omega_8 = \frac{1}{\sqrt{6}}(\bar{u}u + \bar{d}d - 2\bar{s}s) \end{cases} \xrightarrow{m_s >> m_u, m_d} \begin{cases} \omega = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d) \\ \phi = (\bar{s}s) \end{cases} .$$

The origin of ideal mixing can be understood using correlation functions. For that purpose, consider two currents $\omega_1 = \bar{q}q + \bar{s}s$ and $\omega_3 = \bar{q}q - \bar{s}s$. Here q represents the light quark and s



(b) Connected (c) Disconnected contribution

Figure 1: Ideal mixing for the vector meson

represents the strange quark. We limit the discussion to SU(2), but the argument can be easily generalized to SU(3). Consider the two-dimensional correlation function composed of $\langle(\omega_i)(\omega_j)\rangle$, where $i, j = 1, 3$. The matrix can be written as follows.

$$\begin{pmatrix} a+D & \Delta \\ \Delta & a-D \end{pmatrix}, \tag{1}$$

where $a = \langle(\bar{q}q)(\bar{q}q) + (\bar{s}s)(\bar{s}s)$, $\Delta = \langle(\bar{q}q)(\bar{q}q) - (\bar{s}s)(\bar{s}s)$, and $D = \langle 2(\bar{q}q)(\bar{s}s)\rangle$. Δ determines the magnitude of SU(3) symmetry breaking, while D has contributions from disconnected quark diagrams only. The connected and disconnected are diagrammatically represented in Fig. 1-(b) and (c), respectively. The magnitude of mixing between the 1 and 2 components is determined by the relative strength between Δ and D. When $\Delta = 0$, one has flavor symmetry and there are no mixing. When $D = 0$ corresponds to the limit where the quark disconnect contribution is zero. In this case, the matrix can be diagonalized with eigenvalues equal to $a \pm \Delta$, which corresponds to the ideal limit.

$$\begin{pmatrix} a+D & \Delta \\ \Delta & a-D \end{pmatrix} \to \begin{pmatrix} \langle 2(\bar{q}q)(\bar{q}q)\rangle & 0 \\ 0 & \langle 2(\bar{s}s)(\bar{s}s)\rangle \end{pmatrix}. \tag{2}$$

For the vector meson channel, D/Δ is small, and the mixing angle is close to the ideal mixing limit.

3. Chiral Partners

The QCD Lagrangian has SU(3)$_{\rm L}\times$ SU(3)$_{\rm R}$ symmetry when the three flavors are massless. The symmetry can be represented as invariance under $q_{\rm R,L} \longrightarrow \exp\left(i\vec{\theta}_{\rm R,L}(1 \pm \gamma^5)\right) q_{\rm R,L}$, where $\vec{\theta} = \theta^a\lambda^a$

is flavor valued. In the physical QCD vacuum, the chiral symmetry is spontaneously broken.

$$\mathrm{SU(3)_R} \times \mathrm{SU(3)_L} \to \mathrm{SU(3)_V}. \tag{3}$$

This means that the ground state and the physical states will not be invariant under the axial transformation $q \to \exp\left(i\vec{\theta}\gamma^5\right)q$..

Let us consider the transformation of quark bilinears under Eq. (3) when θ is small, for vector currents,

$$\begin{cases} \bar{q}\gamma^\mu\tau^a q & \to \bar{q}\gamma^\mu\tau^a q + \bar{q}i\gamma^5\gamma^\mu\left[\vec{\theta},\tau^a\right]q, \\ \bar{q}\gamma^\mu q & \to \bar{q}\gamma^\mu q + \bar{q}.i\gamma^5\gamma^\mu\left[\vec{\theta},1\right]q = \bar{q}\gamma^\mu q \end{cases}. \tag{4}$$

Therefore, while the vector mesons in the flavor octet representation transform into the axial vector mesons within the octet representation, the flavor singlet vector and axial vector mesons do not transform into each other.

Therefore, when flavor SU(3) symmetry is exact, the vector mesons in the flavor octet representation are chiral partners of the axial vector mesons in the corresponding flavor octet representation. In contrast, the flavor singlet vector and axial vector mesons are not chiral partners.

In the real world where the SU(3) flavor symmetry is broken, and the ϕ and ω mesons are ideally mixed states between flavor octet and singlet components. As a result, they contain components that do not have chiral counterparts and, therefore, cannot be considered chiral partners with their corresponding axial counterparts. One can call these parity partners. One can still discuss the chiral transformation in Eq. (3), where θ is SU(3)-valued, and the flavor octet vector mesons are related to the flavor octet axial vector mesons through chiral transformations. However, since the explicit breaking of SU(3) symmetry is significant in the strangeness direction, it is more appropriate to focus on the chiral transformation limited to the light quark sector, where θ is SU(2)-valued. In this limit, the a_1 is the chiral partner of the ρ, and the K_1 is the chiral partner of the K^*.

4. Chiral symmetry restoration

The broken chiral symmetry is expected to be restored at high temperature and/or density. In general, in addition to chiral symmetry restoration, other effects will occur at finite temperature and/or density. Hence, one can not isolate the effects of chiral symmetry restoration in the mass changes occurring in the individual hadrons. On the other hand, if one studies the chiral partners, all effects other than chiral symmetry breaking will cancel out and the masses of chiral partners will become degenerate.

This means that in the SU(3) symmetric case, all the vector meson masses in the octet will become degenerate with the axial vector meson masses in the same representation. On the other hand, the singlets will become non-degenerate.

In real QCD, where the SU(3) symmetry is broken in the hypercharge direction, one can expect the masses to become degenerate in the SU(2) subspaces as shown Fig. 3. The K^* and ρ mesons will become degenerate with the K_1 and a_1 mesons, respectively. On the other hand, ϕ and ω

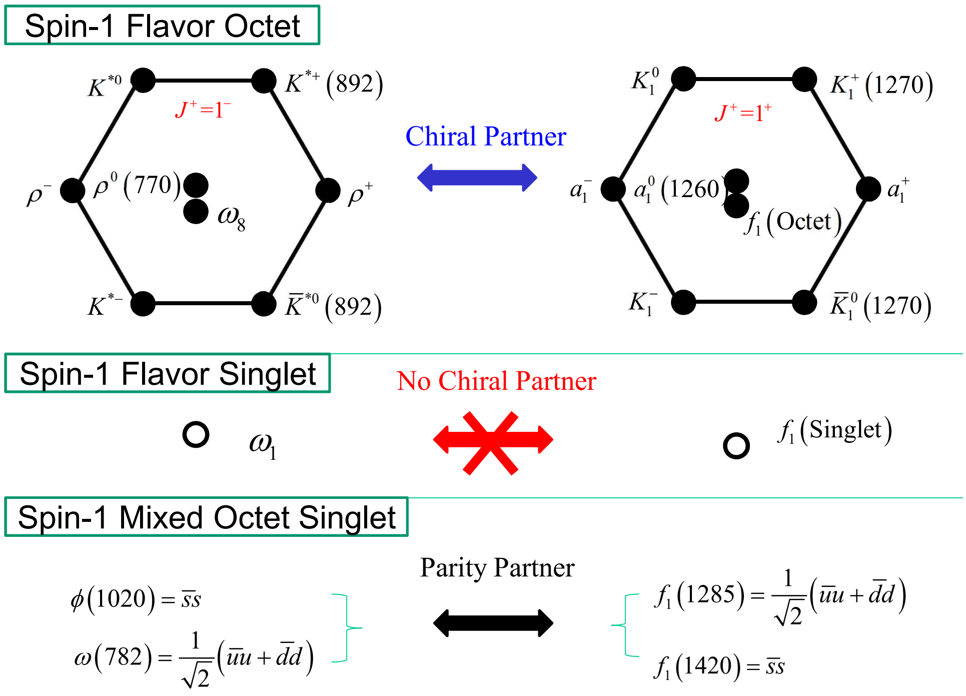


Figure 2: Chiral partners and Parity partners.

mesons will not become degenerate with their corresponding parity partners: namely the $f_1(1420)$ and $f_1(1285)$, respectively. This is because, ϕ and ω mesons are mixed flavor octet and singlet states, the latter of which does not have a chiral partner.

The relation between chiral partners can be well understood in terms of the operator product expansion (OPE)[14]. For example, when one takes the difference between the OPE for the K_1-K^* system, one finds that the difference is a chiral order parameter[15, 16]. On the other hand, when one takes the difference between non-chiral partners, there will be additional contribution from disconnected diagrams that are chirally symmetric.

5. A case for K_1 and K^* in medium

Therefore, to isolate and observe the effects of chiral symmetry restoration, it is essential to observe both particles that are chiral partners. As mentioned earlier, it is particularly important to study mesons with smaller vacuum widths. The ϕ,ω and f_1's have small widths and thus are all interesting states to study. Measuring their medium mass shift will provide important hint on the generation of hadron masses. However, to study chiral symmetry restoration, it is crucial to also investigate chiral partners. As shown in Table 1, among the chiral parter pairs (ρ,a_1) or (K^*,K_1), only the latter pair has vacuum widths small enough to be realistically measurable.

The decay channel that is dominant for the K^* and K_1 mesons are given in Table 2. There are different charge states for the K^* and K_1. The chiral partners are between the same charge states.

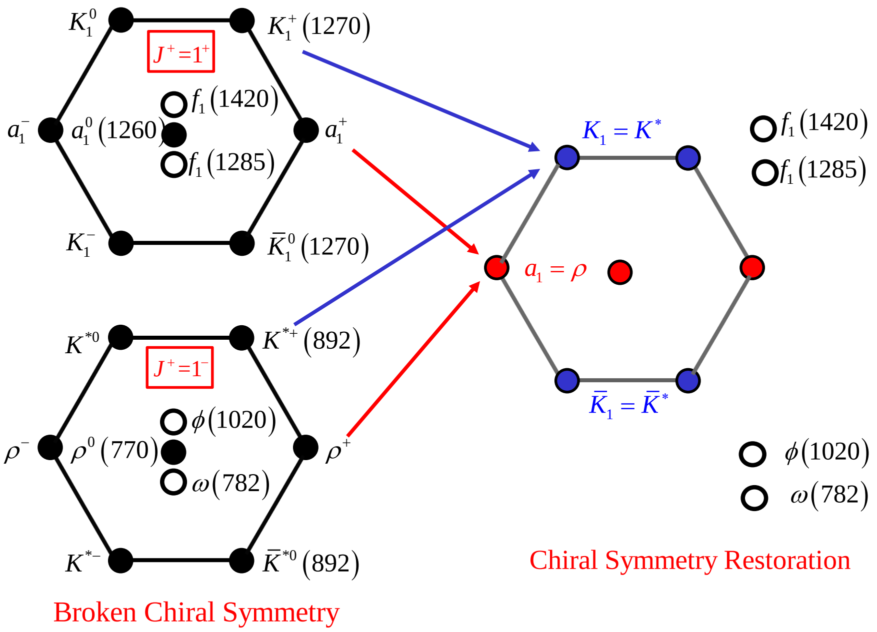


Figure 3: Figure Caption

$J^{PC} = 1^{--}$	Mass	Width	$J^{PC} = 1^{++}$	Mass	Width
ρ	770	150	a_1	1260	250 -600
ω	782	8.49	f_1	1285	24.2
ϕ	1020	4.27	f_1	1420	54.9
$K^*(1^-)$	892	50.3	$K_1(1^+)$	1270	90
$K^*(1^-)$	1410	236	$K_1(1^+)$	1400	174

Table 1: Physical parameters of the vector and axial vector mesons. Units are in MeV$/c^2$.

If the baryon density of the medium is not zero, the different charged states will respond differently irrespective of chiral symmetry restoration. In such an environement, it is important to compare K^* and K_1 with the same flavor states. It should be noted that the ρ and K^* decay into $\pi\pi$ and $K\pi$, respectively. Therefore all the decays can be seen in the $\pi\pi K$ final states. The K_1 are indeed seen in pp event at low multiplicity and are being studied at higher multiplicities at LHC[18] .

The production of both of these particle on a nuclear target can be achieved using the Kaon beam at the JPARC facility. It is important to measure both particles with small velocity because

Table 2: Dominant hadronic decay channels of K^* and K_1 mesons.

1^-	Decay Mode	1^+	Decay mode
$K^*(892)$	$K\pi$ (100%)	$K_1(1270)$	$K\rho$ (42%) $K^*\pi$ (16%)

the spin-1 particles will respond differently whether the spin is alinged parralell or transverse to its motion with respect to the medium at rest. This is so because the mass of the transverse or longitudinal modes will shift in the opposite direction[19, 20]. This effect is dominated by kinematical effect and is not related to chiral symmetry restoration in the medium[14]. One can experimentally separate the transverse and longitudinal modes through the angular dependence of the two-body decay of these particles[21, 22]. Then one can experimentally identify the momentum independent mass shifts. Similar production of both the K^* and K_1 can be achieved by a pion beam at GSI[23].

5.1 K_1 and K^* from heavy ion collisions

The degeneracy between K^* and K_1 mass when chiral symmetry is restored can also be probed in a relativistic heavy ion collision[24, 25]. This is because the initial temperature in an ultra-relativistic heavy-ion collision is expected to be above the transition point to the quark-gluon plasma phase, where chiral symmetry is expected to be restored. As the system cools, hadrons will form at around 156 MeV, as estimated by the statistical hadronization model (SHM) through the observed production of hadron abundances[26]. At this temperature, however, the chiral order parameter is still quite small [27], and since the mass difference depends on the chiral order parameter, the masses of chiral partners will be similar. Since $K*$ and K_1 have the same strangeness, their production ratios will be similar at the hadronization point.

One must still consider the possible changes in particle numbers as the system passes through the hadronic phase. This is known as the hadronic rescattering effect, which typically depends on the vacuum width of the hadron in question. In a central collision, which has a longer hadronic lifetime, the initial K^1/K^* production ratio—close to 1 at the hadronization point—will not be preserved due to hadronic rescattering, which significantly reduces the ratio as the hadrons acquire their vacuum masses at the system evolves in the hadronic phase. If the vacuum masses are used in the SHM, the expected particle ratio between K_1 and K^* will be very small due to the much larger mass of K_1 in the vacuum. However, in peripheral collisions, where the collision region remains dominated by initial temperatures above the transition point, the hadronic lifetime will be shorter, and the anomalously larger initial particle ratio will be visible. Therefore measuring the production of both the K_1 and K^* from heavy ion collision in both central and peripheral collisions, and comparing the observed production ratios to those obtained in the SHM with vacuum masses, will provide a clear signature of chiral symmetry restoration in heavy ion collisions[24, 25].

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